DOI: 10.2436/20.2003.02.208 http://scq.iec.cat/scq/index.html

ISSN 2013-1755, SCQ-IEC **Educació Química EduQ** número 28 (2021), p. 4-11

A teaching-learning progression to introduce the concept of a substance

Una progressió d’ensenyament-aprenentatge per introduir el concepte de substància

Philip Johnson / Consultor d’educació científica

resum

Aquest article presenta una progressió d’ensenyament-aprenentatge que desenvolupa el concepte de substància fins al punt en què les reaccions químiques adquireixen sentit. Desenvolupar un model de partícules és fonamental per a la progressió, atès que aquest model no tan sols explica sinó que també permet predir fenòmens que d’altra manera són impensables per a molts estudiants (l’estat gasós i el canvi químic). La discussió posterior identifica maneres clau en què l’enfocament suggerit és fonamentalment diferent de la pràctica tradicional en l’ensenyament de la química, i com aquestes diferències ofereixen una resposta constructiva a les concepcions alternatives predominants.

paraules clau

Àtoms, partícules, progressió, reaccions, substàncies.

abstract

This article presents a progression which develops the concept of a substance to the point where chemical reactions make sense. A developing particle model is integral to the progression, since this not only explains but also allows predictions of phenomena that are otherwise inconceivable for many learners (the gas state and chemical change). Subsequent discussion identifies key ways in which the suggested approach is fundamentally different to long standing practice in chemistry education, and how these differences offer a constructive response to prevalent misconceptions.

keywords

Atoms, particles, progression, reactions, substances.

Introduction

The current Oxford English Dictionary defines chemistry as «the branch of science concerned with the substances of which matter is composed, the investigation of their properties and reactions, and the use of such reactions to form new substances». This definition seems straightforward, but its sense depends on understanding the meaning of *substances*. To the uninitiated, this is not at all obvious. Individual substances as the constituents of matter (*stuff*, in common language) are not easily recognised from everyday observations. What is meant by *a substance* can be developed with increasing degrees of sophistication.

This article suggests a progression to develop the concept of a substance to the point where various reactions can be recognised. The progression is informed by the body of research into learners’ thinking (Tsaparlis & Sevian, 2013). Paying attention to learners’ perspectives helps to identify necessary steps which are easily taken for granted by those already familiar with the content. An important feature of the progression is the interplay between a developing particle model and learners’ conceptions of macroscopic observations. Discussion then considers how the progression differs from what are assumed to be long standing practices in chemistry education. It will be argued that these differences address well known misconceptions. The discussion closes with comments on implementing the progression in the classroom.

A progression to develop the concept of a substance

Stage 1: Kinds of stuff

Objects and naming kinds of stuff

Distinguishing between an object and the stuff allows naming kinds of stuff. E.g., chopping up a wooden table destroys the table (the object) but each of the pieces is still wood (the stuff). Different objects can be made of the same stuff. Alternatively, the same object can be made of different kinds of stuff. Kinds of stuff are recognised by certain properties.

Families of stuff

Names such as *wood* and *metal* refer to *families*, where members share characteristic properties. Oak and beech are kinds of wood. Copper and gold are kinds of metal.

Some properties depend on the kind of stuff only and some depend on the object as well

Common salt tastes the same for all pieces. A ball of plasticine sinks in water, but the same amount in a boat shape can float. For a beam bridging a gap, how much it bends under a load depends on the kind of stuff, the amount (thickness) and its cross-sectional shape.

Stage 2: Substances and states

Objects/pieces/drops are *samples* of stuff.

Melting behaviour can identify a pure sample of a substance

On heating, pieces of some kinds of stuff change to liquid at a certain temperature, known as its melting point. Below this temperature the sample is in the solid state and above in the liquid state. At melting point, the sample changes from solid to liquid if gaining energy, or from liquid to solid if losing energy. Melting point only depends on the kind of stuff (not the object).

A well-defined melting point indicates a pure sample of a substance. Different substances have different melting points. Other kinds of stuff change from solid to liquid over a range of temperatures (e.g. butter). These are mixtures of substances.

A basic particle model to explain melting

There are three components; *substance particles*, *hold* and *energy of movement*. Substance particles are extremely small and do not have the properties of what is seen. They are unlike anything we know. Substance particles have an inherent ability to hold on to their own kind. Particles of different substances have different abilities to hold, ranging from very low to very high. (Initially, holds between particles of different substances are not considered.) Movement could be vibrating, rotating or travelling. Heating a sample gives the particles more energy for movement. Movement energy is connected to the temperature of a sample. Usually, heating results in rising temperature.

Holding ability and energy of movement act in opposition: hold restricts movement and energy promotes. The state of a substance sample depends on the balance between them. If holding ability dominates, the particles are held close together in fixed places, with movement restricted to vibration. This is the solid state. If hold and energy are more equal, the particles are still close together, but not in fixed places. The particles are able to rotate and travel from place to place as well. This is the liquid state.

Raising the temperature of a sample doesn't affect holding ability, but increases movement energy. Melting is when the particles have enough energy to overcome the hold partially and start moving around. The scenario plays in reverse for liquid state changing to solid state on losing energy. Individual particles do not change so the substance doesn't change. Across different substances, the higher the ability to hold, the higher the melting point. Mixtures don't melt sharply because different kinds of particles interfere with each other.

(At this stage our model does not explain why temperature stays the same during change of state.)

Using the particle model to predict the gas state

What might happen on continued heating of the liquid state? If particles gain more energy, could they overcome the hold completely and separate from each other? Seal a little water (0.5 ml) in a flat, transparent roasting bag. Place in a pre-heated oven at 200 ^{O}C. Very quickly, the bag inflates until all drops of water have disappeared. The space inside is clear- like air. Remove the bag and it collapses immediately, misting up on the inside. Water can change between the liquid and gas states. For boiling water, the large bubbles are water in the gas state.

Pure samples of substances have a well defined boiling point. Above this temperature a pure sample is in the gas state. At boiling point a sample changes from liquid to gas if gaining energy or from gas to liquid if losing energy. For the gas state, particles are far apart. Since the particles are the substance there is empty space (nothing) in-between. Individual particles do not change so it is still the same substance.

Substances with low holding ability have low melting and boiling points. Those with boiling points below room temperature exist in the gas state at room temperature.

Crystals

Pure samples of substances in the solid state form crystals.

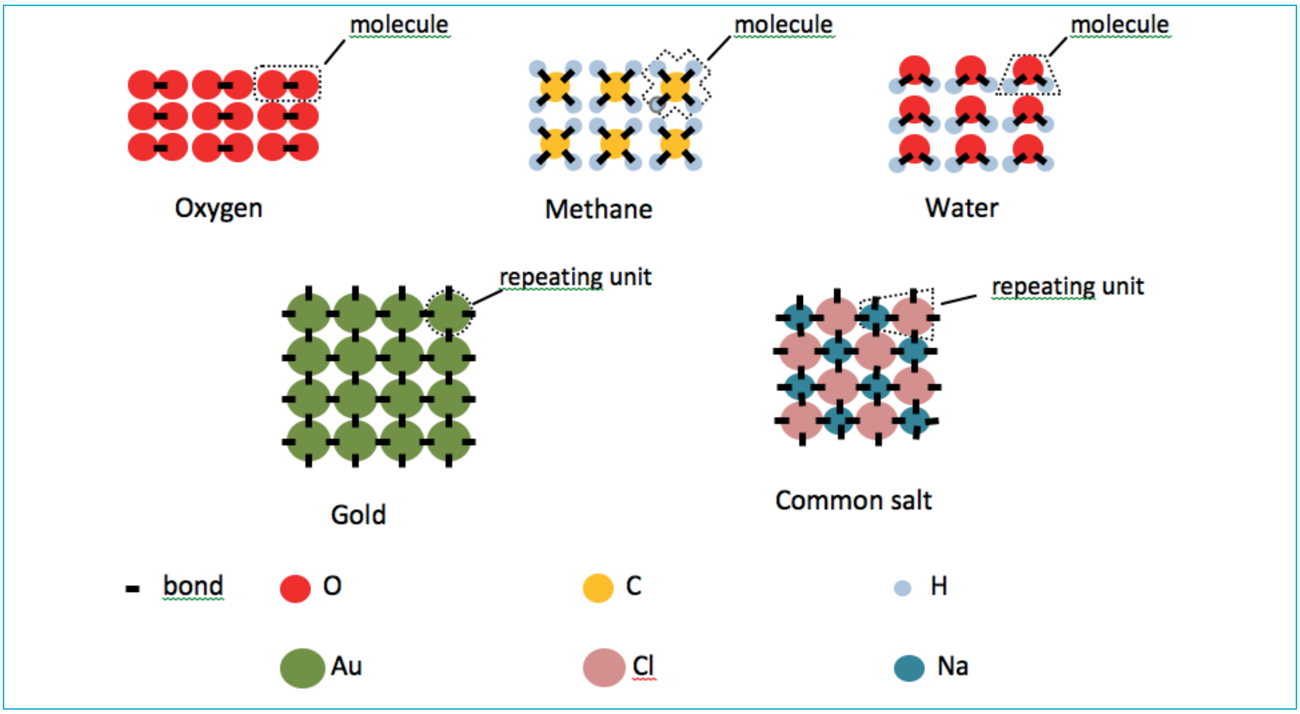

Figure 1. Atom structures of five substances.

Shapes derive from the ordered arrangement of substance particles. The faster they form within a sample the smaller their individual size. If very small, the sample is a powder. When a sample in liquid state solidifies, crystals interlock (e.g. in lumps of metal and blocks of ice).

Stage 3: Substances mixing

Samples of substances can dissolve in water to form a solution

Individual particles of the dissolved substance are mixed amongst the water particles. Whether the added substance sample starts in the solid, liquid or gas states, the solution particle arrangements are essentially the same. The intrinsic motion of particles means mixing is spontaneous.

Solubility is how much will dissolve in a certain amount of water. Solubilities of different substances range from extremely low to unlimited. For practical purposes, those with extremely low solubilities are regarded as being 'insoluble'. For many substances solubility increases with temperature, for others it goes down and some are hardly effected.

Air has a low solubility, which decreases with temperature. Tiny bubbles appearing when cold water is first heated are air coming out of solution.

(At this stage our model cannot explain different solubilities. How particles of different substances hold on to each other is part of the explanation.)

A sample of a substance in the liquid state evaporates into the air, spontaneously

Evaporation is different to boiling. Boiling creates a *pure sample* in the gas state (the bubbles) and happens at a certain temperature. Evaporation results in a *mixture* of the substance and air particles and takes place at any temperature between melting and boiling.

Samples of substances in the gas state mix spontaneously

Air is a mixture of substances which have boiling points well below room temperature. We often refer to *air* without distinguishing between substances. Dissolved air has more oxygen than normal air.

Developing the energy component of our particle model to reconcile evaporation and boiling

If boiling is when particles have enough energy to overcome the hold, how can they separate at lower temperatures for evaporation? At any moment, particles don't have the same energy because amounts are exchanged in collisions. There is a range of energies. To simplify, we can think of low, medium and high energy categories. Temperature relates to the *distribution* across the categories. At a higher temperature more of the particles have high energy and fewer have low energy.

In a non-boiling sample of water, high energy particles at the surface can overcome the hold and escape. Simultaneously, lower energy water particles are ejected by hits from high energy air particles (energy is transferred). Water particles at the surface leave individually, some helped by air particles. For boiling, the water particles act alone. Making the space for some water to be in the gas state (a bubble), needs a number of particles simultaneously overcoming the hold to move apart and push outwards. At a certain temperature there are enough particles with high enough energy to do this.

For evaporation, our model explains how surface area and temperature affect the rate of particles leaving. Recognising the possibility of water particles returning explains the effect of a breeze. Observed evaporation is the difference between rates of leaving and returning. A breeze reduces the rate of return.

Stage 4: Substances undergoing chemical changes

Developing our particle model with the ideas of atoms and bonds

Substance particles are made of *atoms*. There are different kinds of atom. Most atoms have the ability to form holds called *bonds*. These are usually strong. Atoms can bond with their own kind and other kinds. Fig. 1 shows some examples. All are in the solid state. Atom kinds are identified by a letter symbol.

There are two kinds of structure. For oxygen, water and methane, atoms are bonded in groups called *molecules*. There are no bonds between atoms in different molecules. These are *molecular structures*. For gold and common salt there are no molecules. Atoms are bonded continuously. These are *giant structures*. In all cases atoms are bonded throughout in a set way. This is why each is one substance. For molecular structures the molecule defines the substance. For giant structures the repeating unit of the pattern defines the substance. The two types of structure explain the wide range of melting and boiling points.

For molecular structures the arrangement and movement of molecules gives the state. There are relatively weak holds between molecules. These strengthen with more atoms per molecule. Substances with 2-5 atoms per molecule are usually in the gas state at room temperature. Water is an exception. The hold between water molecules is strong enough to raise its boiling point above room temperature. More generally, molecules with O-H bonds have quite strong inter-molecular holds (water has two per molecule).

With giant structures, each atom is held in place by bonds to other atoms. Bonds are usually strong to very strong so this gives giant structures high to very high melting points. (Mercury with relatively weak bonds is a notable exception.) When common salt melts the atoms are able to move around individually, but the bonds mean one kind of atom always surrounds the other. Atoms of the same kind are never right next to each other. (This is to explain why melted salt isn't a mixture.) For the gas state, energies are so high that the bonds can only hold two atoms (of different kinds) together at a time.

Some giant structures are more complex: e.g. calcium carbonate (fig 2). The groups of one C atom and 3 O atoms are like molecules but they *cannot exist on their own* as a substance. They have to be bonded to another atom, like Ca, in a giant structure.

The same kind of atom can make more than one substance. For example O atoms can bond in pairs to make oxygen, or in threes to make ozone. Ozone and oxygen are different substances. They have different melting and boiling points. Just the three kinds, C, O and H, can make an almost unlimited number of substances.

Using the idea of atoms to predict the possibility of substances changing into different substances

Sometimes, when substances encounter each other, bonds between atoms re-arrange. The old substances (reactants) cease to exist and new substances (products) are created. This is known as *chemical change*. The process is called a *chemical reaction*. For example, fig. 3 shows calcium and water changed to calcium hydroxide and hydrogen.

Some reactions occur by just putting substances in contact. Some only occur if the reactants are heated to a higher temperature. Some only occur if one or all of the reactants are dissolved in water. Once started, many reactions give out energy. Some take in energy.

Observations depend on the states of reactants and products at the temperature of the reaction, and whether they stay separate or mix. Reactions that release a lot of energy can get hot enough to give out light as well. For reactions in water, the solubilities of the substances are important. Products with high solubility will be in solution. Those with very low solubility will either appear as a precipitate (if in the solid state), a separate layer of liquid, or bubbles (if in the gas state). Products with medium solubility will be part in and part out of solution, depending on the amount of water.

Decomposition on heating a substance

Some substances undergo chemical change when heated by themselves. For example, calcium carbonate changes to calcium oxide (a giant structure) and carbon dioxide (molecular). We say it decomposes. This happens at a temperature before melting. Calcium carbonate doesn't have a melting point, but it is still a substance. Common sugar decomposes at a temperature just above its melting point.

Differences to customary practice

Fundamental differences to customary practice relate to the notion of substance particles, the role of particle theory in learning, and the importance of distinguishing between elements and compounds.

Substance particles

Introducing a *particle model for substances* gives particles an identity which is independent from sample state and necessitates accounting for different melting and boiling points. In contrast, customary practice begins by categorising room temperature samples into *solids, liquids and gases*. (There is no distinction between substances and mixtures of substances. This, itself, is unsatisfactory since some mixtures have intermediate properties.) When particles are introduced they are identified by these categories. Thus, the particles of *solids* are called *solid particles*, those of *liquids* are *liquid particles* and those of *gases* are *gas particles*. Learners can come to think that *solids*, *liquids* and *gases* are three separate types of stuff, each with its own type of generic particle (a common misconception). Quite literally, *solid particles* are *solid*, *liquid particles* are *liquid* and *gas particles* are *gas* (whatever that is). If individual particles have the observable macroscopic characteristics, the model is not explaining the state and can seem pointless. When stuff melts the individual particles simply melt. The key point about the particle model is that we don't need to say what the individual particles are like as *stuff*.

In the *substance approach*, holding ability is pivotal. It determines the strength of hold when particles are close together and hence the state according to movement energy. (Inherent holding ability doesn't change when particles are further apart and forces are weaker.) In the *solids, liquids and gases approach* learners can easily think that the type of stuff determines the strengths of forces. Forces are strong in *solids* because the stuff is *a solid*, and so on. In this view, ideas of forces don't challenge the notion of three types of stuff and play a subservient role.

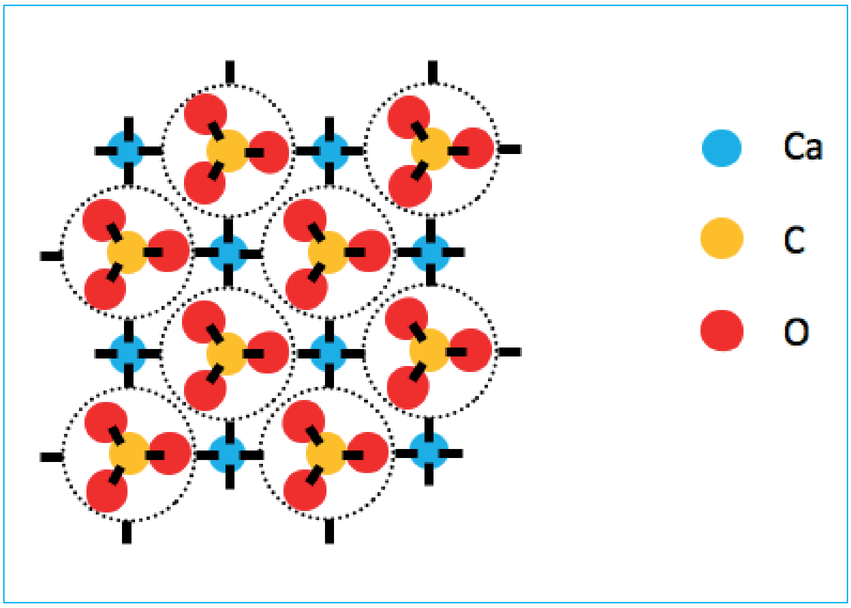

Figure 2. Calcium carbonate.

The *solids, liquids* and *gases approach* with its generic *solid, liquid* and *gas* particles does not distinguish between pure samples of substances and mixtures. Therefore, boiling and evaporation below boiling point are both defined as a change to *gas*. Yes, particles separate in both cases, but why boiling needs a specific temperature and evaporation doesn't is unexplained and confusing to learners. How can heating water to 100 °C or leaving it alone give the same result? The *substance approach* recognises that they don't. Boiling gives a pure sample in the gas state, evaporation gives a mixture. Evaporation into the air is treated as a mixing phenomenon, similar to dissolving. We do not say salt changes to *liquid* when it dissolves. In the *substance approach*, changes of state are for pure sample to pure sample, only. The particle model explanations for the factors affecting rates of dissolving parallel those for evaporation (where stirring is equivalent to a breeze).

Identifying particles with substances means that different shapes and sizes for different substance particles can be used in diagrammatic representations of the states and mixtures. (Shapes can anticipate outlines of atom arrangements defining substances, as picked out in fig. 1.) For want of a reason to choose otherwise, the *solids, liquids and gases approach* normally uses circles. Non-circular shapes make it much easier to represent liquid state disorder while keeping particles close together because they can show random orientations (just using ovals makes a big difference). In *the solid, liquid and gas approach*, diagrams tend to put circles too far apart for the liquid state. Learners can then think spacing is the key difference between solid and liquid rather than movement (particles become closer when ice melts). Misleading emphasis on spacing in the liquid state can also be encouraged by talk of *saturated solutions* which gives a sense of filling up the space.

Role of particle theory in learning

Customary practice presumes *gases* are a known category of stuff, to be explained by particle theory. However, learners find gases to be very mysterious and are far from thinking they are *stuff*

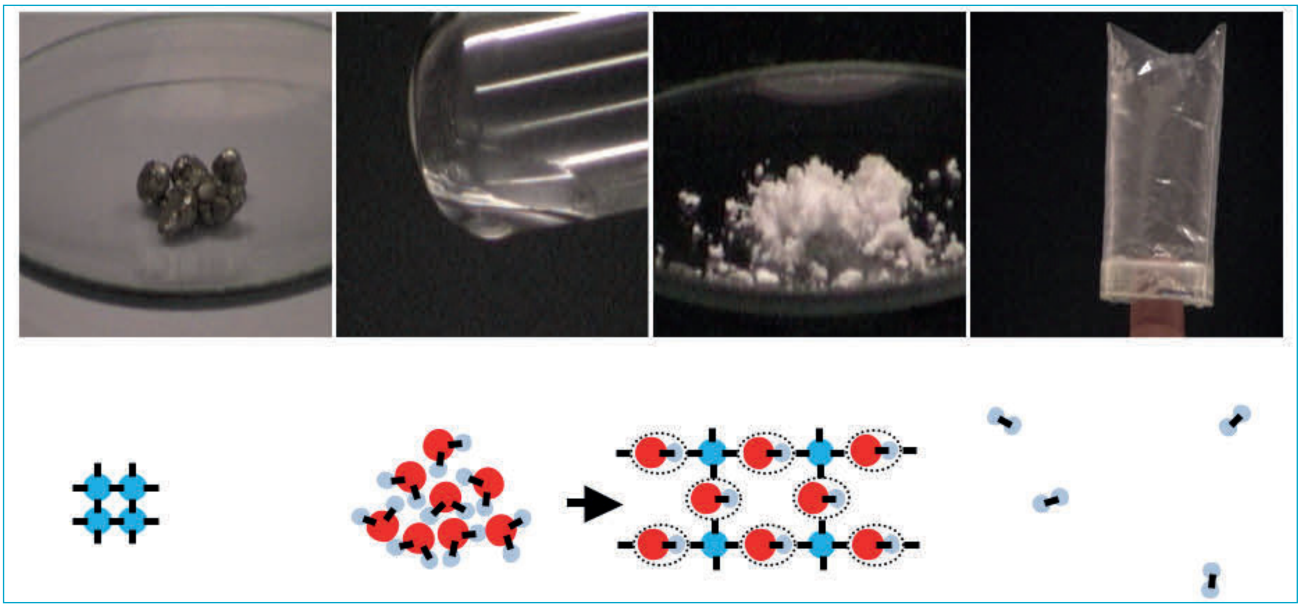

Figure 3. A chemical change: calcium and water changing to calcium hydroxide and hydrogen.

in the same way that *solids* and *liquids* are *stuff*. For *gases*, most learners don't have a conception of what the particle theory is supposed to be explaining. In the absence of knowing water can change to a body of gas, many students say the bubbles in boiling water are *air*. They can say *air* because the bubbles look like air, without knowing what *air* is. Longitudinal evidence (Johnson, 2005) suggests that particle ideas are the means by which learners can begin to think about *gases* as being stuff. Therefore, the suggested progression uses the particle model to predict the *possibility* of the gas state. Seeing a drop of water changing to a large, clear volume in the gas state is a vital experiment. It opens the door to understanding that samples of *gases* are substances just as much as a lump of iron. A *gas* sample just happens to be above its boiling point at room temperature. Water in the gas state is like most other substances in the gas state, which is why the bubbles in boiling water look like air! The successful prediction vindicates the model and illustrates testing of models in scientific practice.

Learners are also mystified by chemical change. Even when appearances and properties change markedly, learners do not see this as a change of substances. Take the example in fig. 3. For many the white powder is either calcium in a different form or a mixture of calcium and water (two substances). Few would say a new substance that isn't calcium or water (Johnson and Tymms 2010). Longitudinal evidence (Johnson 2005) suggests that ideas of atoms are the means by which learners come to accept chemical change as a phenomenon. Therefore, the suggested progression introduces ideas of atoms and predicts the *possibility* of chemical change *before* looking at examples. If we stop to consider, it is a big deal to say that *new* means not existing before. Learners need reasons to believe substances can go out of and come into existence.

Customary practice usually introduces structures and types of bonding together. Considering structures first explains the wide range of holding abilities and gives something for types of bonding to build on, later. By including complex giant structures, the model covers substances commonly encountered in school chemistry.

Overall, there is no attempt to explain how ideas of substance particles and atoms arose. The justification is in the power of the model to explain.

Elements and compounds

The suggested progression makes no mention of elements and compounds. Clearly, the distinction between atom structures made from one kind of atom and those made from two or more kinds could be made. However, for the purposes of explaining chemical change this is unnecessary. All are substances as defined by their atom structures, equally. (When the distinction is made I would call them *elementary substances* and *compound substances*.)

That the same kind or kinds of atom can make more than one atom structure, i.e. more than one substance, is very important. It emphasises the distinction between single atoms that are not substances (except the rare gases) and bonded atom structures that are substances. Furthermore, the properties of substances must derive from the way atoms are bonded together, not what they are like individually. This prepares the ground for the next stage of the progression: ideas of atomic structure and types of bonding.

Atoms have been named after one of the substances made from the kind, usually the first to be discovered. Presumably, oxygen atoms would be called ozone atoms if ozone had come first (and had been called ozone). Unfortunately, having the same name for a kind of atom and an elementary substance conflates the very important distinction. If we say water is made *of* hydrogen and oxygen we are talking about atoms. However, if learners take *hydrogen* and *oxygen* to mean substances, that sounds like a mixture. If we say water is made *from* hydrogen and oxygen we could be talking about atoms (as in a molecule) or substances (as in a reaction). Atoms bond, substances react. Sense can be made if one already knows, but it is easy to see how learners could become quite confused. As exemplified in the suggested progression, I would recommend using names for substances and letter symbols to identify atoms. Then, one has to think about which to use and the meaning is much clearer.

The common term, *pure substance,* also doesn't help. Taken literally, this implies *substances* can be pure or impure which encourages the misconception of elements being pure and compounds being mixtures. The suggested progression always refers to pure *samples* of substances.

Implementation

From a young age, children learn to recognise kinds of stuff by look, smell, taste, and manipulation (how heavy, stretchy and bendy). Stage 1 formalises these experiences and takes them further. Investigating various properties with an increasing degree of sophistication gives plenty to do.

Stage 2 requires judgment on when to introduce particle ideas. A short duration, small-scale study with 9-10 year olds using the substance approach gave encouraging results (Johnson and Papageorgiou, 2011). Longitudinal evidence (Johnson, 2005) has shown how learners' understanding of the particle model develops over multiple interventions spanning years (ages 11-14, in a substance-based approach). Learners need time take aspects on board until they can relinquish all thoughts of individual particles being like the macroscopic substance. With the initial focus on melting, new experiments, demonstrations and videos featuring a range of substances are needed. Candle wax is pure enough to exhibit sharp melting at a low enough point for investigation with a hot water bath. Chocolate provides a contrast. Lead is readily melted and poured out to re-solidify ('freeze') almost instantly (on a thick metal plate).Three burners together can melt common salt (large crystals work best).

In addition to supporting the interpretation of the mixing aspects in chemical reactions, Stage 3 provides an opportunity to consolidate the particle model. Much familiar content can be used to develop the ideas: e.g. separation techniques, with an eye on the purity of resulting samples. Ways of growing crystals can be investigated. Also, how evaporated water in air starts to separate from the mixture on cooling, at a temperature which depends on the concentration of water. As well as mists, exploration of mixtures could extend to others where substances do not mix at the level of individual particles; such as gels, pastes, emulsions, foams, and smoke. If felt appropriate, the idea of energy distribution could be left until later. It doesn't sit on a direct line to interpreting observations surrounding chemical change, though is the basis for understanding rates of reaction. If desired, the discussion can develop the idea of pressure within a body of gas and how boiling point depends on the external pressure.

Stage 4 can follow when learners are ready, probably around ages 13- 14. Here examples should be chosen to illustrate different combinations in terms of numbers of substances, their states or in solution and whether heating is needed to start the reaction. Different ways of making the same substance challenges learners' propensity to think of products as either reactants in a different form or in a mixture. For all reactions, I would recommend starting and finishing with separate pure samples of all substances involved (as in fig. 3). Most customary school experiments actually don't. Often, reactants are not seen before solutions are made and some products are not recovered from solution. Oxygen is taken from the air unnoticed. Fig. 4 shows oxygen in a bag. As the magnesium reacts the bag collapses. Formulae and balanced equations stem naturally from bonded atom structure representations of chemical reactions.

Stuff and Substance: Ten key practicals in chemistry (Johnson, 2011) is a free downloadable resource directed at developing the concept of a substance.

Finally, while showing the power of the developing particle model, it is important to recognise what it cannot account for, yet. We still need to explain why temperature stays the same during changes of state, why there is such a range of solubilities and different temperature

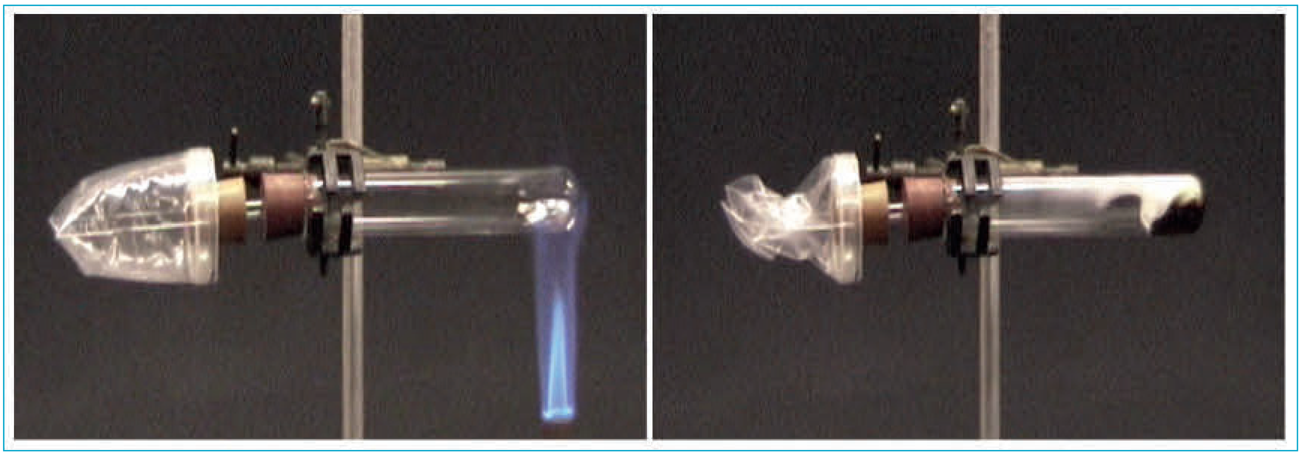

Figure 4. Magnesium reacting with oxygen.

effects, and, indeed, why chemical reactions happen. Ultimately, these require the idea of entropy (Johnson, 2018).

Conclusion

This article opened with a definition of chemistry. It seems uncontroversial to suggest that a basic understanding of this definition should be the main, initial goal of chemistry education. Without an understanding of *substances* that recognises the possibilities of three states, mixing and chemical change, how else could the stock of chemical knowledge make sense? The suggested progression plots a route to achieve this goal. Other routes could be devised, but melting behaviour provides a readily accessible, outward sign of purity to build on. It is difficult to think of a suitable alternative. Crystals are not always obvious. Solubility doesn't discriminate. From melting the course is essentially set by the hierarchical relationship between ideas. Rather than being a constraint, the suggested progression invites chemistry education to explore suitable ways of teaching the ideas with a free choice of stimulating activities and content. This might mean adapting old experiments or finding new ones that better illustrate certain features. With ideas having primacy, assimilating certain pieces of information is of much lesser importance. The pacing can be adjusted to suit the learners. Of course, there is always the danger of learners developing misconceptions. However, compared to customary practice, the progression offers a constructive response to many prevalent misconceptions and may even prevent some arising. With an introductory curriculum based on the suggested progression, I believe there is good reason to have high expectations of learners.

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Philip Johnson

He graduated with a chemistry degree from Imperial College and taught chemistry for thirteen years in 11-18 UK comprehensive schools before joining Durham University School of Education. He is now retired. He began researching into the development of students' understanding in chemistry while teaching in schools and continues to do so. He conducted a three year longitudinal study for his PhD, awarded by Durham.
Email: *p.m.johnson@durham.ac.uk*